Development of Astronomy Large Focal plane Array “ALFA” at Sofradir and CEA

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ABSTRACT

CEA and Sofradir have been involved for 7 years in studies related to a large format detector development for science and astronomy applications. These studies are linked with ESA's Near Infrared Large Format Sensor Array roadmap which aims to develop a 2Kx2K large format low flux low noise device.

The ALFA (Astronomical Large Focal plane Array) detector is currently at design, manufacturing and validation phase at CEA and Sofradir. This paper will present the very last achievements of the ALFA development with a specific focus on the readout integrated circuit design itself. Features and specification of the 2048x2048 15µm pitch with Source Follower Detector (SFD) input stage will be described.

Apart from ESA development, European Commission is also contributing to the large detector development thanks to ASTEROID (AStronomical TEchnology EuROpean Infrared detector Development) program founded by REA (Research European Agency). ASTEROID main objectives are to develop very large raw materials (CdZnTe substrate, HgCdTe epilayer…) compatible with the manufacturing of very large detectors in volume keeping the same level of performance. Organization and status of this program will be presented where high synergy with 2K² ALFA detector are included.

Keywords: Infrared detectors, dark current, quantum efficiency, low flux, low noise, large format

1. INTRODUCTION

ALFA detector design is done and the ROIC is now under manufacturing. After reminding the previous ESA studies performed at CEA-LETI, CEA-IRFU and Sofradir, this paper will describe the expected performances and design features of the ALFA 2048x2048 15µm pitch Read-Out Integrated Circuit (ROIC). Then a presentation of the first application for ALFA detector will be done : the COLIBRI Telescope for SVOM mission, its organization, objectives, instrumentation and detector requirement. Finally we will focus on the program funded by European Commission, ASTEROID (AStronomical TEchnology EuROpean Infrared detector Development) detailing its objectives, organization and first results.

2. REMINDERS

2.1 ALFA DETECTOR SPECIFICATIONS

Since years, ESA wishes to have a European large size detector available for scientific missions. Indeed, ESA started several studies in order to develop a technology answering this need. The last study which has been started aims to scale-up this technology to a large-sized prototype detector. This detector, named as per its funding activity Astronomy Large Format Array (ALFA), shall have the same performances as the detectors tested in the frame of NIRLFSA phase 2, which was ESA previous study, based on a 640x512 15µm-pitch detector. The main parameters expected are synthetized in Table 1.

Parameter	Value
Array size - pitch	2048x2048 – 15µm
Spectral range	Cut-on ≤ 0.8µm, cut-off 2.1µm / 2.5µm
Operating temperature	100 ± 1 K
Quantum efficiency	≥ 70%
Dark current (at 100K)	≤ 0.1 e-/pix/s
Linear well capacity	≥ 60ke-
Non linearity	≤ 3%
Cross talk : inter pixel capacitance / other contributions	≤ 2% / ≤ 3%
Readout noise (single CDS)	≤ 18e- rms
Readout speed	≥ 100kHz

Table 1 Main specifications of the ALFA detector

The first challenge of this activity concerns the ROIC development, because it is a new ROIC design, implementing some specificities linked to scientific applications, and also particularly for its fabrication, as such component size requires using the stitching technique at foundry level in order to go beyond the pholithographic mask size. A second challenging aspect is regarding the hybridization process. Today, the largest hybridized arrays existing at Sofradir are sized 1280x1024 15µm pitch, called Jupiter, and 1024x1024 15µm pitch named NGP (both shown in Figure 1), which is quarter the size of the ALFA component. Hybridization techniques have to be improved for such large format.

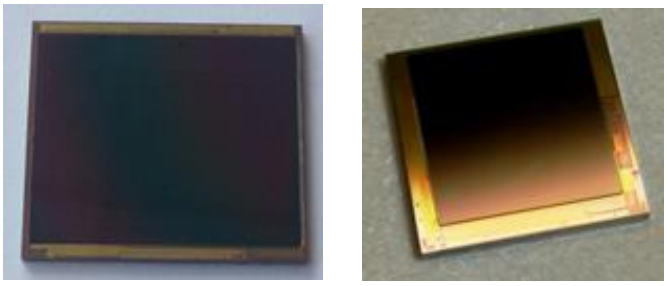


Figure 1 Jupiter FPA (1280x1024, 15µm pitch) - NGP FPA (1024x1024, 15µm pitch)

Last but not least, the detector is able to be compatible with buttability requirement, aiming to set several components the one close to the other with a minimum space between sensitive areas to achieve a very large multi-detector mosaic focal plane array. This specification has also to be taken into account in the development.

2.2 DEVELOPMENTS AND RESULTS OF PREVIOUS PHASES

2.2.1 Technological developments

Different parameters led the technological developments. Aside from the large format (this parameter had not been addressed at the time of NIRLFSA studies at CEA nor at Sofradir), what matters above all for such detectors are the very high level of performance in QE, dark current and noise. While the noise is mainly addressed by the ROIC input stage, QE and dark current are highly depending on the photodiode structure. Photocarriers absorption and collection must be optimized in order to get high QE: high pixel fill factor is required as well as thick enough absorbing layer. Concerning dark current, at the low operating temperatures considered here, dark currents are most likely depletion currents related to SRH recombination defects in the space charge region of the photodiode [1]. The mitigation of such depletion currents implies the best material quality as well as the best narrow gap surface passivation. These have been the main drivers for photodiode developments concerning scientific low flux detection.

The p-on-n photodiodes architecture discussed in the present paper is very similar to the diode structure in the H2RG device, a well-known focal plane array in the astronomy community. The absorbing material is the versatile HgCdTe (MCT) narrow gap semiconductor alloy, doped n-type. Photodiodes are formed with As ion implantation resulting in reticulated planar p-on-n structures (see Figure 2 right). Photons are mainly absorbed in the n-type absorbing layer. Once absorbed, the resulting photocarriers diffuse up to the p-on-n junction to be collected thus forming the photocurrent that will be the useful signal of the pixel. Hence, such a structure might be qualified as a “diffusion extracted p-on-n planar photodiode”. As opposed to the H2RG device that makes use of a wide gap cap layer MBE grown, LETI photodiodes involve only one single layer of narrow gap MCT. This layer may be grown by horizontal-slider liquid phase epitaxy (LPE) in rich-Te solution or by molecular beam epitaxy (MBE). Both growth technics have been investigated in this work. Refer to [2] for more details.

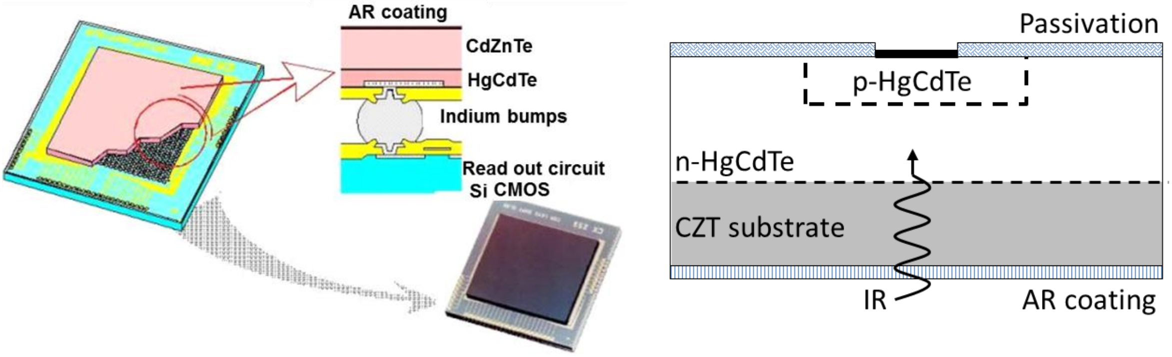


Figure 2 Schematic representation of the MCT P on N photodiodes and arrays

Concerning the ROIC, a very popular input stage for low flux imaging is the source follower per detector (SFD) where the integration is carried out onto the diode capacitance itself. The diode is connected to a MOS in follower mode to achieve high impedance. During the integration time, the capacitance of the diode is slowly discharged as the photo electrons are collected and integrated into the diode capacitance.

Our SFD ROIC was first designed by Sofradir [4] then extended to larger formats at LETI using the same philosophy [5].

2.2.2 Detector performances

The performances measured on the devices are presented in detail in [2], this paragraph summarizes the results obtained.

Two devices (one using MBE growth technique and one using LPE) were fully characterized at CEA. For both detectors, all parameters were measured at the same operating point, 100K operating temperature and 400mV diode bias. These detectors have a size of 640x512 pixels of 15µm pitch, with p/n structure diodes and a SFD input stage ROIC.

2.2.2.1 Quantum efficiency

The quantum efficiency was measured in three different ways. The QE measured at 80K at CEA-LETI on test vehicles is shown in Figure 3 for two different wafers, PV3367 corresponding to the LPE growth, and PV3369 corresponding to the MBE growth. The actual cut-off wavelength was very close to the expected one (2.1µm) and the cut-on wavelength was 800nm since the substrate was not removed. The measurement of the LPE device (black triangle data points) confirms the value obtained at CEA, between 70 and 80% over the whole spectral range. These values are very close to the QE of the H2RG device.

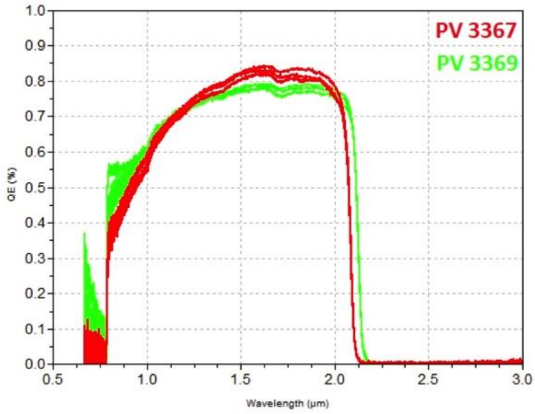


Figure 3 QE as measured at CEA-LETI on test vehicles

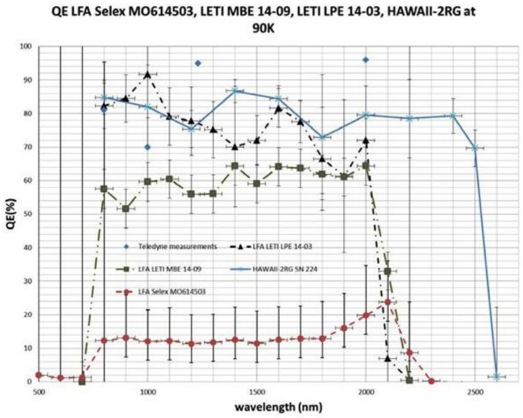


Figure 4 QE measured at ESA on delivered detectors

2.2.2.2 Readout noise

The readout noise was measured on 60s and 600s integrations in dark conditions. Three readout modes were used, correlated double sampling (CDS), Fowler-32 and up the ramp with 150 nondestructive readouts (FUR-150). Noise was measured on both test pixels and diode pixels. In CDS mode, the readout noise measured on the test pixels is very good, at 11.4 and 11.5 e- rms for the two devices. The reduction of noise given by the Fowler-32 mode works as expected, but the FUR-150 mode does not work as well, giving a noise about twice the expected value.

2.2.2.3 Dark current

The measurements were performed using nondestructive readouts, from 40K to 160K. The dark current is derived from a linear regression fit.

The dark currents measured on both the LPE and MBE devices at 100K are about 1.1 e-/s/pixel. The map of the current at dark for the MBE detector is shown in Figure 5. The eight video outputs of the detector are located near the top of the imaging area. It is clear from the map that the detector suffers from a strong glow, at a level of 10 to 20 e-/s/pixel near the outputs, all the way across the detector. The same glow was measured on all devices. In order to check the origin of the current, the same measurement was performed after some optimization of the ROIC operating point. The current is halved, from 1.2 to 0.6 e-/s/pixel (Figure 6), but it is clear from the map shown in Figure 7 that the glow is still present.

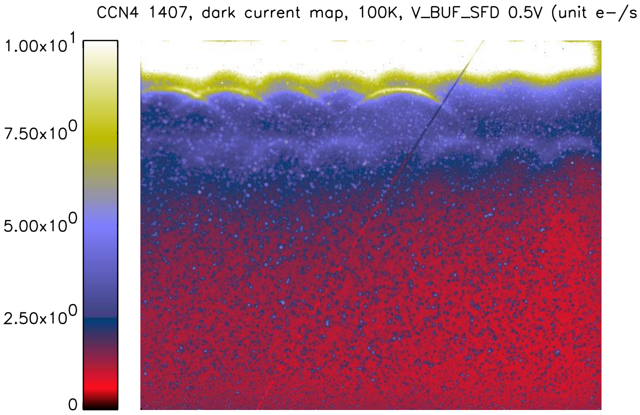


Figure 5 Current map at dark for the MBE device at 100K, nominal ROIC bias voltages

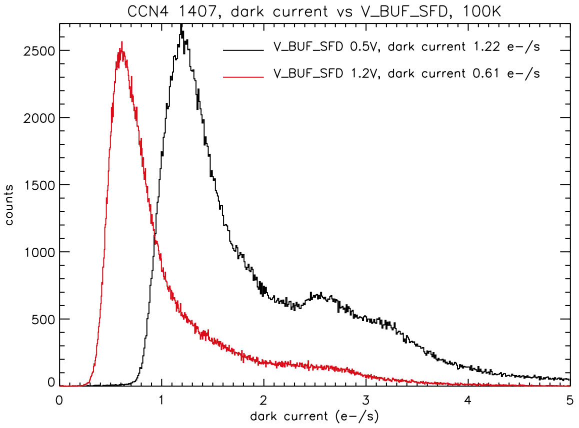


Figure 6 Distribution of current at dark as a function of video output current

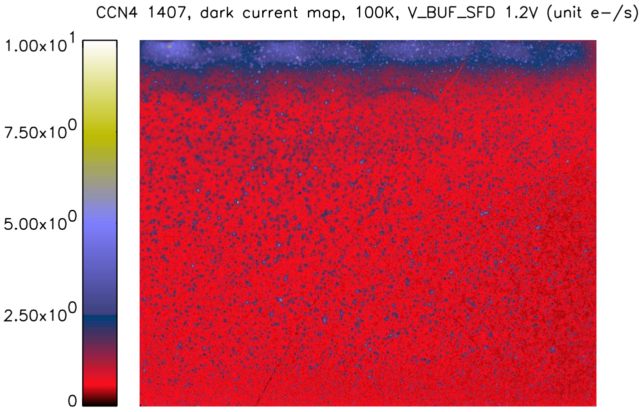


Figure 7 Current map at dark for the MBE device at 100K, after some ROIC optimization

Because of this high level of glow, it is very difficult to assess the actual level of dark current but it is clear that for both the LPE and MBE devices at 100K, the dark current is much less than 0.5 e-/s/pixel.

2.2.2.4 Performances summary

The table below summarizes the performances measured on the devices at CEA-IRFU:

Parameter	Value
Operating wavelength	0.8- 2.1µm
Cutoff wavelength	2.1µm
Quantum efficiency	74% mean value
Operating temperature	100K
Dark current (at 100K)	<0.5e-/s
Linear well capacity	60ke-
Non-Linearity	3.2% and 2.5%
Cross talk (inter pixel capacitance)	0.6% to 1.1%
Readout noise (single CDS)	11.4 to 11.5e-
Readout speed	100kHz

3. FOCUS ON ALFA COMPONENT

3.1 ALFA ROIC

3.1.1 ROIC architecture

As presented in the previous chapter, it has been demonstrated that the performances obtained by CEA/Sofradir prototypes in the previous ESA development phases are in line with the requests. Readout noise is lower than 12 e-, non-linearity mean value is 3% and capacitance of the CMOS pixel in the ROIC is very low (typically 5fF) in order to minimize the readout noise. The pixel design of the Source Follower per Detector (SFD) input stage used both on 384x288 15µm and 640x480 15µm are thus compatible with the final need. This building block is therefore able to be used for designing the full scale 2k² detector. The other conclusion of these previous phases is that special considerations are necessary in the design phase in order to limit the glow effect seen on the TV/4 size prototypes.

The ALFA ROIC is composed by a matrix of 2048 by 2048 pixels with 15µm pitch. Therefore its overall size is close to 30x30 mm². In order to achieve such dimension, the stitching technique has been implemented in foundry. The validation of this technique is very important for future ROIC developments, as from now there is no more limitation on ROIC size.

ALFA ROIC architecture is given in Figure 8: in green the analog parts, while in blue the digital ones. The data are provided through 32 outputs, more a reference output which is linked to a pixel not connected to photodiode: this pixel is maintained under the reference bias level.

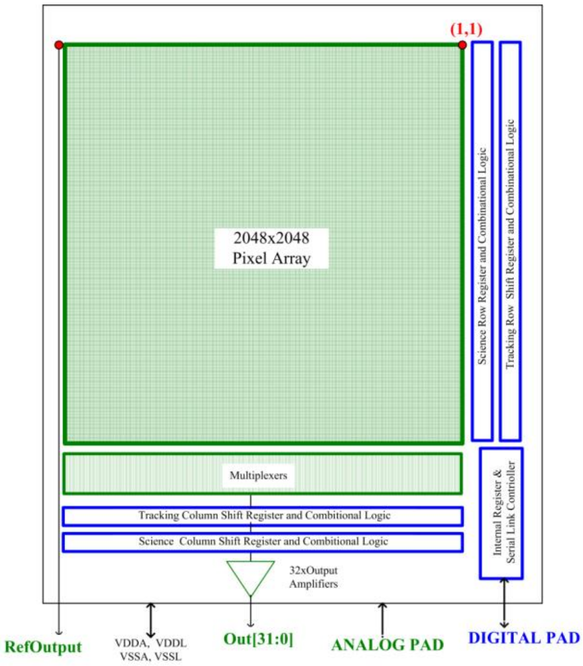
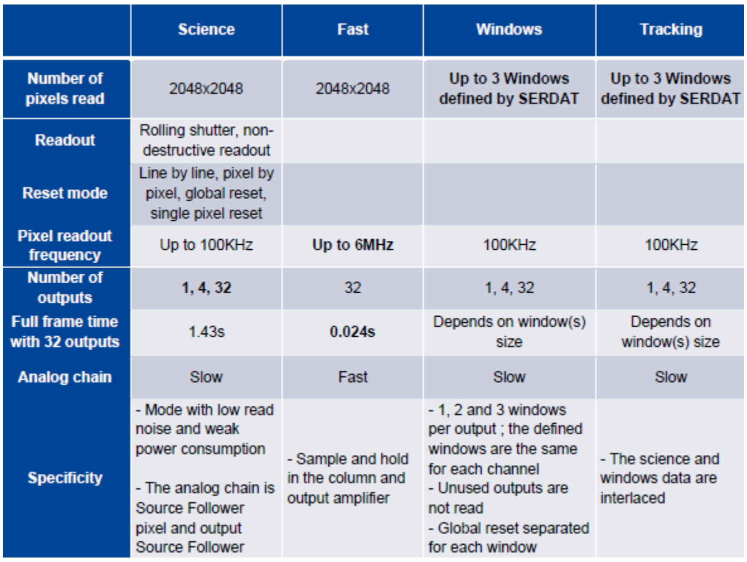


Figure 8 ALFA ROIC architecture

3.1.2 ROIC operating modes

ALFA ROIC has four operating modes. The default one, called Science mode, allows the user to get images of the full matrix with its best performances (low noise, low power consumption, weak glow generation) with a readout frequency up to 100kHz. The data are available with 1, or 4 or 32 outputs. In order to operate the detector faster, a Fast mode is available, with a readout frequency up to 6MHz, giving a full frame reading time of 24µs with 32 outputs. The Window mode allows defining and reading up to 3 windows with adjustable sizes, as well as the Tracking mode which is an interlaced readout of the full field and the windows. Main characteristics of each mode are given in Table 2.



	Science	Fast	Windows	Tracking
Number of pixels read	2048x2048	2048x2048	Up to 3 Windows defined by SERDAT	Up to 3 Windows defined by SERDAT
Readout	Rolling shutter, non-destructive readout			
Reset mode	Line by line, pixel by pixel, global reset, single pixel reset			
Pixel readout frequency	Up to 100KHz	**Up to 6MHz**	100KHz	100KHz
Number of outputs	**1, 4, 32**	32	1, 4, 32	1, 4, 32
Full frame time with 32 outputs	1.43s	**0.024s**	Depends on window(s) size	Depends on window(s) size
Analog chain	Slow	Fast	Slow	Slow
Specificity	- Mode with low read noise and weak power consumption - The analog chain is Source Follower pixel and output Source Follower	- Sample and hold in the column and output amplifier	- 1, 2 and 3 windows per output ; the defined windows are the same for each channel - Unused outputs are not read - Global reset separated for each window	- The science and windows data are interlaced

Table 2 Operating modes main characteristics

Thanks to SFD input stage, the ROIC readout mode is a non-destructive readout, and there are several types of reset, all available in both full frame modes and windowing modes. Indeed, the reset can be done on each pixel individually, or line by line, or also on the full frame/window.

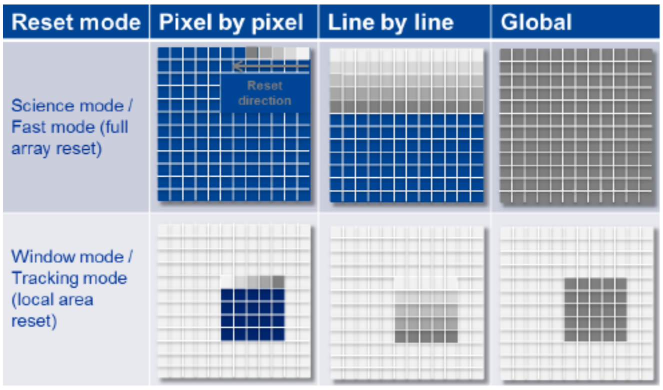


Figure 9 ROIC reset types

To ease the detector characterization, features have been added in the ROIC design. As an example, in order to measure the interpixel capacitance (IPC), the user can select unitary pixels which shall be maintained under reset. With IPC ='1' in Serial Link, the user programs a pattern thanks to the crossing of signals HWINLOAD (Column Selection) and VWINLOAD (Row Selection). This pattern defines the pixels which are maintained under reset and the ones which integrate the scene flux. Thus the matrix array is read and the interpixel parasitic capacitance can be found. Then all pixels of the matrix array can be characterized by varying this pattern. Figure 10 provides an example of IPC test.

	1	0	1	1	0	0	1	0
1	1	0	1	1	0	0	1	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
1	1	0	1	1	0	0	1	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
1	1	0	1	1	0	0	1	0
1	1	0	1	1	0	0	1	0

Figure 10 IPC example

3.1.3 ROIC expected performances

3.1.3.1 Power consumption

The expected average power consumption of ALFA ROIC during a readout is presented here below according to the number of outputs, for a readout frequency of 100 kHz and external current source (default mode).

	Nb Out=1 [2]	Nb Out=4 [2]	Nb Out=32	Units
Total consumption	0.18	0.25	0.85	mA
	0.6	0.82	2.8	mW

Table 3 ROIC power consumption in Science mode

In Fast mode (32 outputs operating at a readout frequency of 6 MHz), the power consumption is as following:

	Value	Units
Total consumption	30	mA
	100	mW

Table 4 ROIC power consumption in Fast mode

3.1.3.2 Charge handling capacity (CHC) and linearity

The estimated value of CHC for ALFA ROIC is 135ke-.

A first simulation has been launched in order to measure the linearity of the analog chain in Science mode. The linearity evaluation is given in Figure 11.

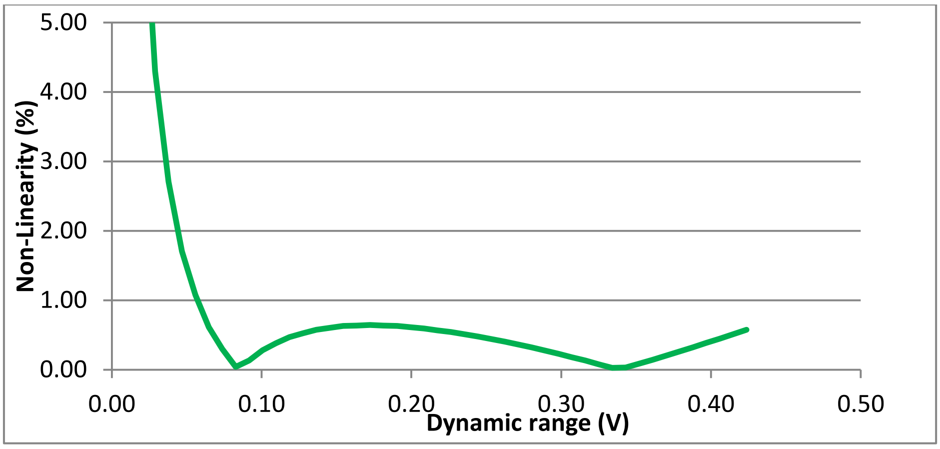


Figure 11 Linearity of analog chain in Science mode

The non-linearity error is lower than 1% for most of the useful range of the ROIC

3.1.3.3 Readout noise

Based on the analog chain in Science mode, ALFA ROIC noise has been estimated by:

$$Read\ noise^2 = SF\ noise^2 + OUT\ noise^2$$

With:

- SFnoise : noise of Source Follower pixel
- OUTnoise : noise of the output stage

A first simulation in small-signal analysis gives:

- SFnoise = 15µVrms
- OUTnoise =15µVrms.

If an external CDS is done and considering that this method is equivalent to a high-pass filter, the low frequency noise can be reduced, as well as the Flicker noise and the KT/C noise, but the high frequency noise and the thermal noise will be increased by √2. Hence the read noise is estimated to 11e-.

3.1.3.4 Cross-talk

Depending on the input stage architecture, parasitic capacitors between adjacent photodiodes (in the photo-detector circuit) may or not have an impact on the crosstalk. SFD input stages mainly suffer from these parasitic capacitors. The information on flux is obtained in these stages by reading out their operating voltage changes onto the photodiode capacitors. Thus a capacitive coupling between for instance a highly illuminated photodiode and a non-illuminated adjacent photodiode will induce a voltage change in that non-illuminated photodiode, and will thus be seen as a variation of its operating point due to an input flux. The IPC mode can be used in order to evaluate this capacitor.

The preliminary estimations show a crosstalk inferior to 3%.

3.1.3.5 Glow prevention

As seen in the previous phases of study, dark current measurement is hardly achievable because the circuit emits a radiation, commonly called glow, which is basically at a level higher than the dark current level. By the way, to be able to perform the dark current measurements on ALFA ROIC, some elements have been implemented in the design. Indeed, starting from the design of LETI ROIC previously studied, efforts have been done in order to reduce the power consumption, as it can be noticed in 3.1.3.1. Moreover, some design rules have been also implemented in order to reduce as far as possible this “parasitic” flux.

3.1.3.6 Performances summary

The table below summarizes the performances expected for ALFA ROIC:

Parameter	Goal value	Evaluated value
Size	2048 x 2048	2048 x 2048
Pitch	15 x 15 µm²	15 x 15 µm²
Output number	32	1, 4, 32
Linear well charge handling capacity (CHC)	≤ 60 ke-	135 ke-
Non-Linearity	≤ 3%	< 3%
Readout noise (single CDS)	≤ 18e- rms	~ 11e-
Cross-talk	≤ 3%	< 3%
Power consumption Science mode (32 output) Fast mode	 < 50 mW @ 70K NS	 3 mW 100 mW
Readout speed	≥ 100 kHz	100 kHz

As one can see, the simulation results show that ALFA ROIC fits with ESA requirements, hence it is well adapted to science applications.

3.2 MATERIAL GROWTH AND PHOTODIODE PROCESSING

The requirements for the PV process are different for Astronomy application than for the defence applications usually considered for p on n MCT photodiodes at Sofradir. Those differences lie in the large size of the arrays, but also on the low flux application requirements and last but not the least, on the specificity of the ROIC input stage that has to be taken into account in the photodiodes design.

Indeed, the arrays considered here are much larger (3x3cm²~10cm²) than the usual 1 cm² class detector used for tactical applications. With the need of processing yield and therefore the will to processed several arrays onto the same wafer, this larger size requires a dramatic increase in the size of the processed wafers, from 5x5cm class wafer up to at least larger than 7x7cm wafers, while guaranteeing the high uniformity in performance across such large wafers. At LETI and Sofradir, before the photodiode processing and packaging, CZT substrate and MCT sensitive layers are grown in-house. Hence, such a scaling to this larger size implies deep changes in the growth and processing steps, with a complete revision of the whole fabrication chain.

This revision begins with the CZT substrate growth performed by vertical gradient freeze (VGF) bulk method. Since several years now, current boules grown at LETI and Sofradir are above 110mm in diameters, while maintaining the very high crystalline quality required for MCT growth (DDX width in the mid 20s arcsec), low dislocation density (in the low $10^4 cm^{-2}$) and low precipitate concentration [7] Crystalline orientation is set to 111 in order to perform the liquid phase epitaxy of the MCT layer onto this substrate. The Zn content is optimized to guarantee lattice matching with the targeted SWIR range MCT composition (2.1 and 2.5µm cutoff).

After dicing into 7x7cm wafers, the substrate surface has to be prepared for the LPE growth. Again, this surface preparation has to be optimized for this increase in size, together with the LPE growth itself. This implies a thorough work to maintain uniformity across the wafer (which means larger polishing devices and larger epitaxy machine chambers).

Size matters of course, but absolute performance matters too. Indeed, the high performance level demonstrated in the past [8] has to be kept while scaling up the arrays.

Indeed, the low temperature performances in terms of noise and dark current is mainly determined by defects in the narrow gap MCT material used to sense IR light. Concerning material growth, this supposes to get the best crystalline quality with second order lattice matching between the CZT substrate and the MCT sensitive layer, as mentioned previously. This high quality material layer must then be carefully passivated by dielectric layers in order to limit as much as possible the potential material degradation of the interfaces during the photodiode technology, thus minimizing interface generation-recombination and associated dark currents and QE losses.

Last but not least, as opposed to direct injection (DI) or trans-impedance amplifiers (CTIA) input stages, in the SFD architecture used here, the photo-charge integration is carried out onto the diode capacitance itself. Therefore, the bias voltage of each pixel varies during integration. Moreover, this bias variation may vary differently from pixel to pixel depending on the charge distribution in the sensitive layer. In this case, capacitive coupling between neighbouring pixel appears of first importance as it may become as strong source of cross talk. As a matter of consequence, interpixel capacitance (IPC) is of first importance here and its value is carefully monitored as it depends on the interconnection geometry but also on fixed or mobile charges in the passivation layer. Another key specific parameter is the persistence, which is also taken into account in the development of the ALFA photodiode process. Indeed, in SFD systems, the space charge region is expected to extend differently from one frame to the other one (depending on the flux evolution). Trapping – detrapping in the vicinity of this variable depletion region may introduce persistence issues from one image to the next ones, and are also taken into account in the diode design and process.

4. COLIBRI: FIRST ALFA DETECTOR MISSION

4.1 SCIENTIFIC CONTEXT

At all times, the study of cosmic explosions has been connected with key advances in astronomy. This is especially true now that cosmic explosions are used as standard candles to pace the Universe (type Ia supernovae), as probes of the distant Universe (Gamma-Ray Bursts - GRBs), as extreme physics laboratories (relativistic jets, production of cosmic rays, etc.), and as the only witnesses of the birth of compact objects (black holes and neutron stars). In the near future, cosmic explosions will stay at the forefront of astrophysics with the maturity of the astrophysics of multi-messengers (neutrinos and gravitational waves) and with the development of time domain (or synoptic) astronomy.

In this scientific context, GRBs play a very specific role, as they are the most energetic explosions in the Universe after the Big Bang. Due to these extreme luminosities, GRBs can be used to probe the most observationally hostile and remote regions of the Universe.

The forthcoming Sino-French SVOM (Space-based multi-band astronomical Variable Objects Monitor) mission will have a major contribution to this scientific domain by improving our understanding of the GRB phenomenon and by allowing their use to understand the infancy of the Universe. It is designed to achieve the best compromise between space and ground instrumentation. The onboard instruments will permit the detection of the GRBs, their localization, the study of the prompt emission and the early detection and follow-up of visible afterglows. The ground segment will permit the fast distribution of the alerts, the localization of GRBs with sub-arcsecond precision and the primary selection of high-redshift candidates ($z > 6$).

The Chinese National Space Agency (CNSA) and the French Space Agency (CNES) have officially decided the SVOM mission. The project is now following a well-established schedule and the launch date is fixed in 2021, with a lifetime of at least 3 years.

In order to fulfill its scientific objectives, the SVOM mission involves a robotic 1-m class ground telescope, COLIBRI, under French responsibility. This one has a very special place in the SVOM system by fulfilling the following functions:

- Guarantee visible to infrared observations of the GRBs from the first minute to at least one day.
- Provide GRB localization with accuracy better than arc-second, less than 5 minutes after the alert reception on the ground (for reference, the localization accuracy of the alert provided by ECLAIRs an onboard instrument is about 26 arc-minutes).
- Provide an identification of low signal to noise triggers, for which a platform slew is not requested. These triggers due to, for example, GRBs highly extinguished or located at very high redshift have potentially a very strong scientific impact.
- Localize and observe dark GRBs, i.e. events detected in gamma, x-ray domains, but not in the visible domain.
- Insure the link between the SVOM satellite and the ground largest facilities, as NTT, VLT, ALMA, etc. by providing an estimation of the GRB redshift 5 minutes after the alert reception.

Figure 12 : View of the GFT site in San Pedro Mártir in Mexico (left). Similar Telescope of COLIBRI (developed and manufactured by ASTELCO, Germany).

These requirements set very strong constraints on the technical specifications: high availability for alert observations, very good sensitivity (1.3 m mirror diameter), fast pointing speed (on target in less than 20 sec after the alert reception), multiband photometric capabilities (from 400 to at least 1800 nm, with three simultaneous bands), and field of view covering the SVOM trigger error box (26 arc-minutes).

The GFT project is a collaboration between France and Mexico. UNAM and CONACyT in Mexico will host COLIBRI at the Observatorio Astronómico Nacional in San Pedro Mártir (OAN/SPM), Baja California, fund the building hosting it, provide the assistance necessary for proper operation and contribute to the instrumentation.

Components of the project like telescope, infrared camera, control center, etc. are supplied by France. They are jointly funded by INSU/CNRS CNES, and the LabExs OCEVU and FOCUS.

COLIBRI will use the sensor developed by SOFRADIR and CEA for the infrared camera, which is under the French responsibility. This camera, named CAGIRE, will image a 26' round field-of-view in a single exposure in either NIR photometric band J or H.

The optical design is presented in Figure 12. It is based on a two-mirrors telescope with field corrector lens feeding a three-channel imager with two visible CCDs and one H2RGs NIR imager.

The distribution of tasks on the project is as follows (by alphabetical order):

- CEA: Characterization of the sensor – Expert Scientist on the camera.
- CPPM: Integration of the sensor with the NGC card developed by ESO – Controller settings and detailed characterization of the sensor with its controller.
- IRAP: Project Management – Development of the cryostat and Control/Command – Integration of the sensor in the cryostat – Detailed characterization of the camera – Integration of the camera at OAN/SPM in Mexico.
- LAM: PI of COLIBRI – System Engineering – Integration of the camera at OAN/SPM in Mexico.

4.2 INSTRUMENT AND DETECTOR REQUIREMENTS

The instrument design is driven by the possibility of direct imaging for the visible channels (i.e., with no reimaging optics). It ensures the right field of view on the detectors and good image quality within the field of view. The following features are relevant for NIR camera, CAGIRE:

- A dichroic separates the visible arms from the NIR arm, defining the short wavelength cutoff of the NIR arm at 1.1 µm.
- Most of the optical elements of the NIR arm are warm, with only one cryogenic lens close to the detector.
- The optical design ensures a cold pupil within the cryostat.

The camera is composed of the following elements:

- The NIR sensor and its electronics.
- A lens located in the cryostat. The tolerances on this element are not really severe: position along revolution axis: ±0.3 mm, misalignment: ±0.8 mm, tilt: ±1°.
- The cryostat.

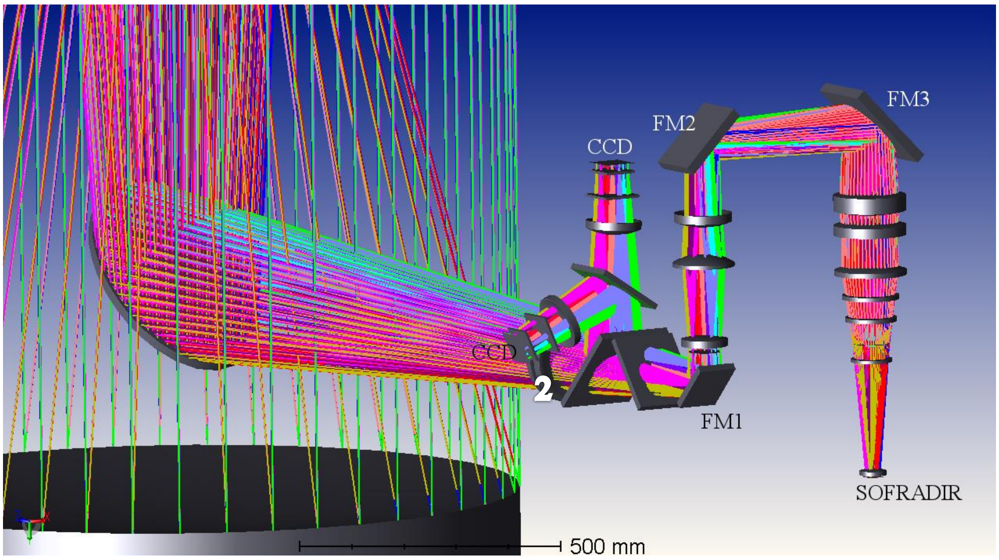


Figure 13: Instrument concept selected for the GFT. The visible arm (CCD) is equipped of two 4kx4k cameras from Spectral Instruments and the infrared arm (SOFRADIR) is equipped of a 2kx2k camera

The infrared camera will be in operation for many years, from mid-2020 to at least 2026.

The main constraints on the infrared camera are given in the table below.

Instrument requirements	
Number of detectors	1
Field of view	26' round
Photometric channels	J & H
Sensitivity	Sky limited
Total thermal background	≤25 % of sky signal
CDS readout noise	< 20e-
Time to start a new observation, when already in operation	≤10 s
Time resolution	≤2 s
Timing accuracy	0.01 s

The performances required are compatible with the expected performances and requirements of the ALFA Sofradir sensor.

Number of pixels	2048 x 2048
Dimension of the pixels	15 x 15 µm
Spectral range	0.8 – 2.1 µm
Operating temperature	<110 K
Readout noise	~20 e-
Full frame readout time	~1.5 s
Well capacity	≥ 6 104 e-
Image latency	< 0.1 %

5. ASTEROID

5.1 PROGRAM PRESENTATION AND OBJECTIVES

The ultimate goal of the ESA study is to develop a full size detector product (ALFA, 2048x2048, 15µm pixel pitch) and finally to have one European IR detector manufacturer ready to propose this NIR/SWIR LFA at production level with the requested level of TRL. Where ALFA program aims at developing the first 2048x2048 15µm pitch detector at Sofradir, ASTEROID goal is to prepare the future technologies ready to produce this detector in volume and also to access larger format detector such as 4K².

In May 2017, ASTEROID program started at Sofradir. This program is founded by the EC (European Commission) in the frame of H2020 development program strategy. REA (Research Executive Agency) follows the program at the EC, Sofradir is leading the program and the management of the consortium. The European consortium is composed of 4 other partners in Europe (see §5.2).

To be able to manufacture very large FPA, 4 key constraints exist. Indeed large FPA require:

- Very large dimension Read Out Integrated Circuits (ROIC)
- Very large substrates (mono-crystalline CdZnTe alloy);
- The capacity to epitaxy high quality HgCdTe material on these substrates;
- A manufacturing line fully compatible with large substrate dimensions.

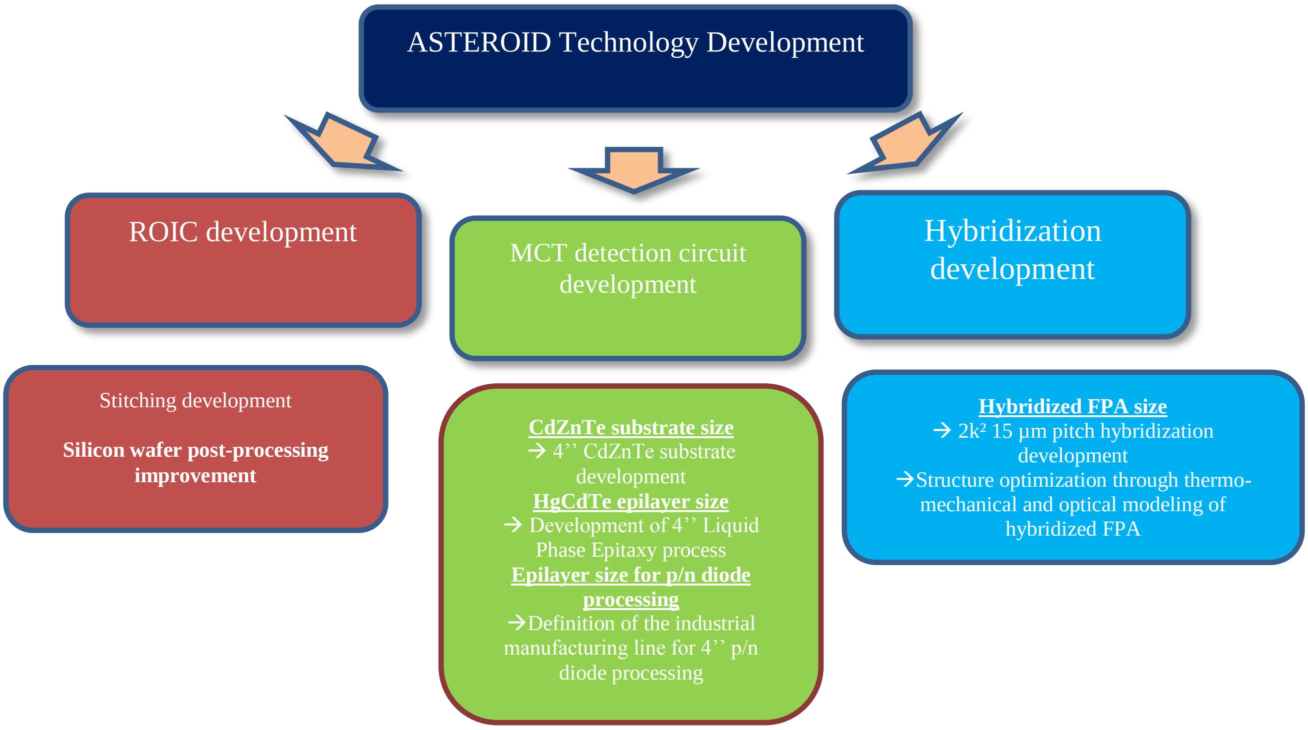
Thus the whole industrial chain must be adapted especially if the number of detectors to produce is important.

The main objective of the ASTEROID project is thus to extend the dimension of high performance infrared FPA that can be manufactured in Europe to dimensions equivalent to that of the US competitors, keeping the same level of performances mentioned in the previous paragraphs. This will allow Europe to become independent for the procurement of this type of detectors. The targeted format is 2k² 15µm pitch FPA (2048x2048 pixels).

The technology required for manufacturing 2k² FPA is composed of 3 essential building blocks.

- ROIC development : Prepare the industrial manufacturing line capable of post-processing CMOS wafers with > 30x30 mm² ROIC
- MCT development: Develop and validate 4’’ CdZnTe substrate technology and develop and validate 4’’ epitaxy. Define an industrial manufacturing line capable of doing p/n processing of 4’’ epilayers
- Hybridization technology : Optimize the hybridization technique for 2k² FPA with 15 µm pitch

The axis of development are summarizes in the next schema



ASTEROID Technology Development

ROIC development

MCT detection circuit development

Hybridization development

Stitching development

Silicon wafer post-processing improvement

CdZnTe substrate size
→ 4’’ CdZnTe substrate development
HgCdTe epilayer size
→ Development of 4’’ Liquid Phase Epitaxy process
Epilayer size for p/n diode processing
→Definition of the industrial manufacturing line for 4’’ p/n diode processing

Hybridized FPA size
→ 2k² 15 µm pitch hybridization development
→Structure optimization through thermo-mechanical and optical modeling of hybridized FPA

5.2 EUROPEAN PARTNERS

The ASTEROID consortium is composed of 5 complementary partners coming from 3 European countries. The following table gives an overview of the different partners’ expertise and complementarity and demonstrate that the consortium is well prepared and committed to fulfil the project’s objectives and achieve its challenges. The ASTEROID consortium consists of an interdisciplinary team from:

- 3 European industrials (SOFRADIR, EVG and SME ADDL)
- 2 research organisations (CEA and IFAE)

Each partner of the project is leaders in their field of application. SOFRADIR is an international leader specialized in IR detectors manufacturing. Research partner CEA will focus on MCT wafer technology and SWIR p/n technology.

EV Group (EVG) is a leading supplier of equipment and process solutions for the manufacture of semiconductors, microelectromechanical systems (MEMS), compound semiconductors, power devices, and nanotechnology devices. Key products include wafer bonding, thin-wafer processing, lithography/nanoimprint lithography (NIL) and metrology equipment, as well as photoresist coaters, cleaners and inspection systems.

Spanish research institute IFAE is specialized in testing with experience, the institute works at the cutting edge of detector technology and has made major contributions at experiments at CERN (ATLAS, ALEPH and several R&D projects), Neutrino physics (T2K), in Gamma-Ray astrophysics (MAGIC, CTA) and Cosmology (DES, DESI, PAU, Euclid).

Finally, the consortium will profit from French SME ADDL which has expertise in finite element modelling. ADDL has developed a high level of expertise in simulation of multiphysics and multiscale systems (solid mechanics, CFD and electromagnetics) using advanced methods such as finite elements, finite volumes and boundary elements.

All partners have an extensive expertise in the field of IR sensors and have been previously involved in several European and national R&D collaborative projects.

ASTEROID is a highly interdisciplinary project, requiring expertise from different backgrounds. Therefore there is a strong interaction between partners with different specialisations:

Partner	Country	Main scientific and technical contribution
SOFRADIR	FRANCE	SOFRADIR is in charge of the global program management as leader of the consortium. SOFRADIR is in charge of the read-out silicon design in collaboration with LETI. The hybridization of the test vehicle will be also performed at SOFRADIR as the expected packaging able to receive the $2k^2$ IRFPA for testing.
CEA	FRANCE	CEA (LETI Institute) will be in charge of the development of scaled up MCT wafers and technology in collaboration with SOFRADIR. Part of the MCT wafers will also be manufactured at SOFRADIR in order to ensure technology transfer at industrial level. CEA (IRFU Institute) will be in charge of the characterization of the SWIR p/n technology as expert in testing high performances IR detectors

EVG	AUSTRIA	EVG will be in charge of process adaptation for scaling up the ROIC manufacturing line at SOFRADIR.
IFAE	SPAIN	IFAE will be in charge of the testing of 2k² hybridized FPA
ADDL	FRANCE	ADLL will be in charge of the FE thermomechanical modeling of the 2k² hybridized structure itself.

The following Figure (Figure 28) depicts the relationships between each partner during the project. This makes it possible to understand the interactions that exist.

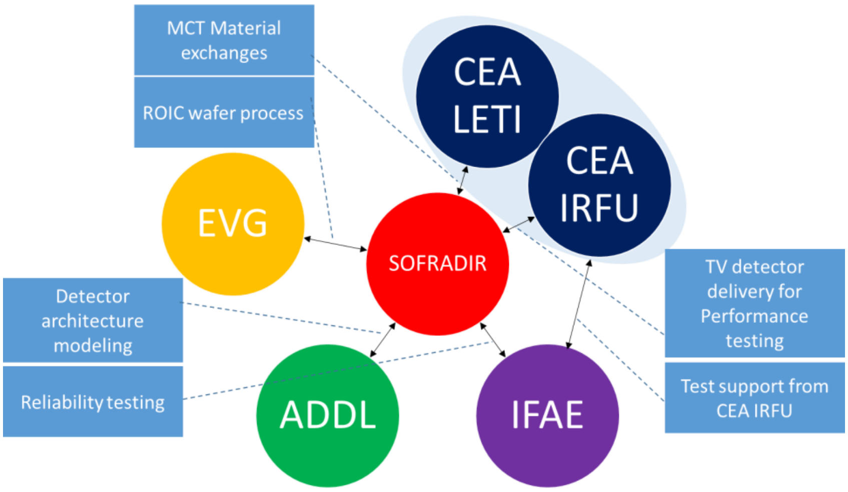
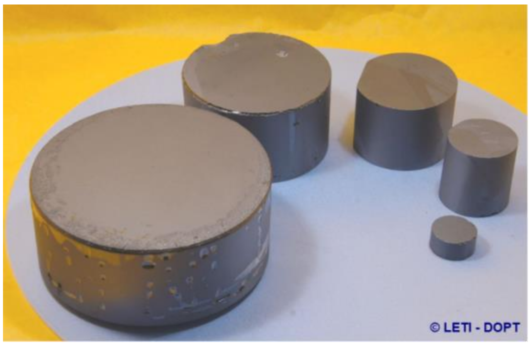


Figure 14: Relationship between each partner

5.3 PROGRESS OF THE PROGRAM

This first part of the program was mainly oriented on the tooling development for manufacturing and testing. But, after one year of progress, Asteroid program has already demonstrated results at CdZnTe ingot growth and post processing. The first ingots with very large size has been done and characterized. With the substrates extracted from these ingots, epitaxy wafer with 4'' size have also been manufactured at CEA LETI as seen in the next figure.



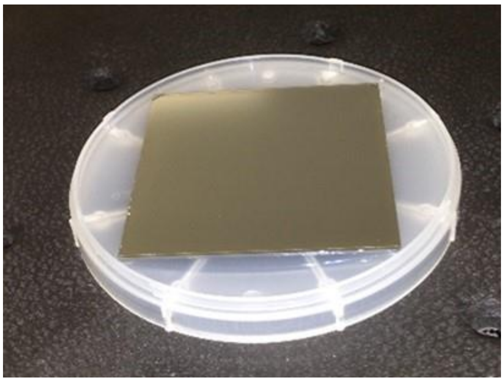


Figure 15 First epilayer of Cd$_{1-y}$Zn$_{y}$Te with a 4’’ format @CEA LETI (Right) in ASTEROID program / Examples of different CdZnTe ingots at CEA-LETI (Left)

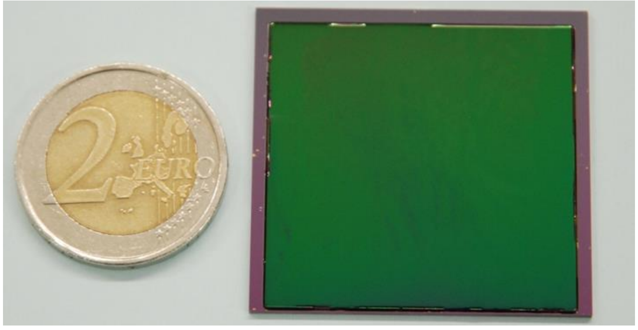


Figure 16 : First hybridized mock-up 2048x2048 manufactured at Sofradir

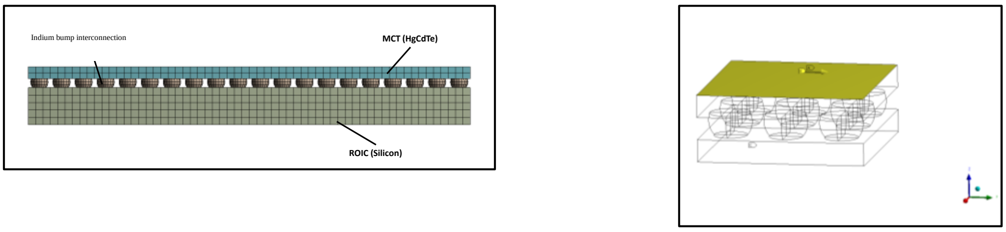


Figure 17 : Illustration of IRFPA simulations

EVG has worked on new Silicon wafer post processes and results are promising for large 8’’ ROIC wafer sizes. The collaboration with Sofradir will help to upgrade the ROIC industrial line taking into account the large wafer size challenge.

ADDL is developing dedicated modeling software in order to assess the thermo-mechanical constraints on the 2K² detector at cold temperature. This evaluation and complex calculations will allow to potentially adapting the hybridization process, post-process, tooling and packaging.

IFAE laboratory and CEA-IRFU have worked on the test plan and mean preparation for next year (2019) tests and characterization.

Sofradir and CEA-LETI have worked on the CdZnTe wafer and 4’’ epitaxy process preparation and Sofradir has also worked on hybridization process adaptation for such large detector. ALFA ROIC wafers will be procured in early September 2018 and first hybridization will be done by the end of the year.

It has to be highlighting here that there are synergies between ALFA programs and ASTEROID as for example, ALFA ROIC wafers and dices will be used to adapt and improve manufacturability processes in the frame of ASTEROID.

6. CONCLUSION

Sofradir and its historical partners CEA-LETI and CEA-IRFU continue to work on the development of complete European solution for infrared astronomy application for ground and space. The first 2048x2048 15µm pitch, ALFA prototype is up to come by end of this year 2018. Extended the core partners to European ones thanks to H2020 funding by European Commission, Sofradir prepares the future industrialization of this detector at major scale. The first ground astronomy application, COLIBRI in SVOM mission, will help ALFA to open a European way for large IR detector for astronomy and science applications.

7. ACKNOWLEDGEMENTS

The authors would like to thank major contributors for the ALFA developments. ESA contract 22949/09/NL/CP, this work has been partially supported by the LabEx FOCUS ANR-11-LABX-0013 . Authors would like also to thank CNES for supporting part of ROIC previous development activity (contract 92871/00) and DGA (French MoD) for continuous developments in large CZT and MCT wafer size domain.

8. REFERENCES

[1]. Gravrand O., Rothman J., Cervera C., Baier N., Lobre C., Zanatta J.P., Boulade O., Moreau V., Fieque B., “HgCdTe Detectors for Space and Science Imaging: General Issues and Latest Achievements”, Journal of Electronic materials, DOI: 10.1007/s11664-016-4516-3 (2016)
[2]. Olivier Boulade, Vincent Moreau, Patrick Mulet, Olivier Gravrand, Cyril Cervera, Jean-Paul Zanatta, Pierre Castelein, Fabrice Guellec, Bruno Fièque, Philippe Chorier, Julien Roumegoux, “Development activities on NIR large format MCT detectors for astrophysics and space science at CEA and SOFRADIR”, Proc SPIE 9915-10 (2016)
[3]. G. Finger, R. Dorn, M. Meyer, L. Mehrgan, A. F. M. Moorwood, and J. Stegmeier, ”Interpixel capacitance in large format CMOS hybrid arrays“, Proc. SPIE 62760F (2006)
[4]. Fièque B., Martineau L., Sanson E., Chorier P., Boulade O., Moreau V., Geoffray H., “Infrared ROIC for very low flux and very low noise applications,” Proc. SPIE 8176, 81761I (2011).
[5]. Guellec, F., Boulade, O., Cervera, C., Moreau, V., Gravrand, O., Rothman, J., & Zanatta, J. (2014). “ROIC development at CEA for SWIR detectors: pixel circuit architectures for space applications and tradeoffs”, ICSO conference (p. 65879), Tenerife (2016).
[6]. Crouzet P.-E., Duvet L., de Wit F., Beaufort T., Blommaert S., Butler B., Van Duinkerken G., ter Haar J., Heijnen J., van der Luijt K., Smit H., “Quantum efficiency performances of the NIR European Large Format Array detectors tested at ESTEC,” Proc. SPIE 9639, 96390X (2015).
[7]. [ref Brellier, D., Gout, E., Gaude, G., Pelenc, D., Ballet, P., Miguet, T., & Manzato, M. C. (2014). Bulk Growth of CdZnTe: Quality Improvement and Size Increase. Journal of Electronic Materials, 43(8), 2901–2907. https://doi.org/10.1007/s11664-014-3146-x].
[8]. [Cervera, C., Boulade, O., Gravrand, O., Lobre, C., Guellec, F., Sanson, E., … Castelein, P. (2016). Ultra-Low Dark Current HgCdTe Detector in SWIR for Space Applications. Journal of Electronic Materials. https://doi.org/10.1007/s11664-016-4936-0]